CREEP OF ICE: FURTHER STUDIES

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In the past year we have completed detailed studies of
(1) the flow of high-pressure water ices II, III, and V, and
(2) frictional sliding of ice I_h. Preprints describing both
studies are now being circulated among interested colleagues
before submittal for publication. In addition, we began
work on the second phase of the current proposal--the study
of the effect of impurities on the flow of ice. We
summarize the results of these three projects below.

Flow of high pressure ice. Over the past two and one-
half years we have tested 36 different samples of high
pressure ice to pressures as high as 550 MPa and
temperatures as low as 158 K. The appropriate portion of
the H_2O phase diagram is shown in Figure 1. From our tests
we have derived 77 independent measurements of strength
(flow stress as a function of temperature, confining
pressure, and strain rate) and a
host of other data related to
phase transformation kinetics and
phase metastability in ice. The
flow results for ices II, III,
and V are summarized in Figure 2.
Ice II is the strongest of the
phases, having a strength
slightly higher than that of ice
I_h, and ice III is the weakest.
The low strength of ice III is
striking: under a fixed set of
conditions ice III will flow
approximately 100-1000 times
faster than ice II or ice V.
This is important to the
evolution of a large icy moon
such as Ganymede or Callisto. An
ice III layer, situated between a
layer of ice V and a layer of ice
I_h or II, will behave over long
periods essentially as a liquid,
unable to transmit meaningful
levels of shear stress between
the layers bounding it.

We have found that on the
laboratory time scale of a few
days, important metastable
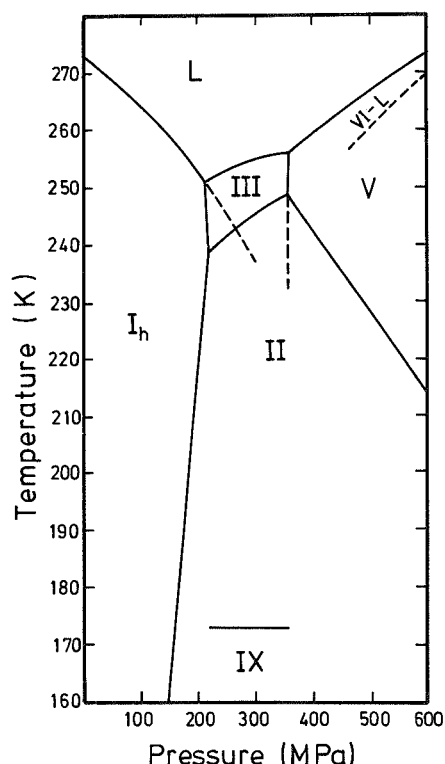relationships exist between the
phases of ice. The strongest of

Fig. 1. H_2O phase diagram.

these is the metastable existence of ice III in the warmer portion of the ice II stability field, a phenomenon known for many decades. What we have found is that these metastabilities endure even under large amounts of deformation, where local structural rearrangements might be expected to seed the transformation from ice III to ice II. Ice III deformed at temperatures as low as 210 K does not revert to II during deformation. The transformation from ice III to V and back (dashed line in Figure 1 at P=350 MPa) can also occur within the ice II

Fig. 2.   Flow of ices II,III,and V

field without producing any sign of ice II, even when the transformation is accompanied by deformation of the sample. Although it seems unlikely that such metastabilities endure over geologic time scales, the point is interesting because of the low strength of ice III and the probability that present and past temperature profiles within the icy moons are very close to the ice II-III phase boundary.

Frictional sliding in ice I_h. We can simulate sliding along existing large-scale faults in the crust of an icy moon by means of triaxial mechanical testing of cylinders of ice composed of two pieces that slide with respect to one another. The Voyager photos suggest such faults exist on the moons' surfaces, so our laboratory data should further constrain evolutionary models of the moons. We performed tests at temperatures from 77 to 115 K, near the expected surface temperatures of the moons, and at confining pressures from 0.3 to 250 MPa. The results from tests at 77 K are shown in Figure 3. Temperature turns out to play no noticeable role in the frictional characteristics of ice, nor does rate of sliding, which varied from 10^{-2} to 10^{-4} mm/s. The variable of overriding importance is the normal
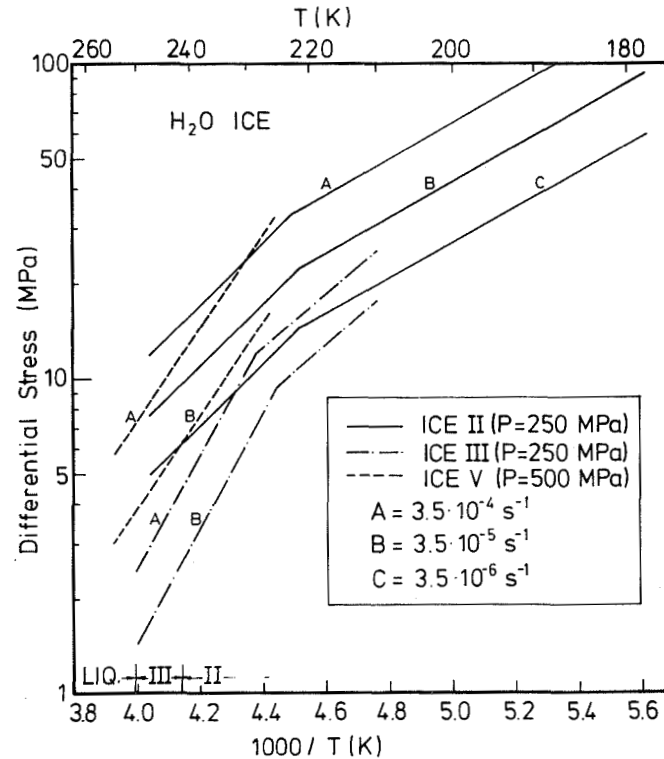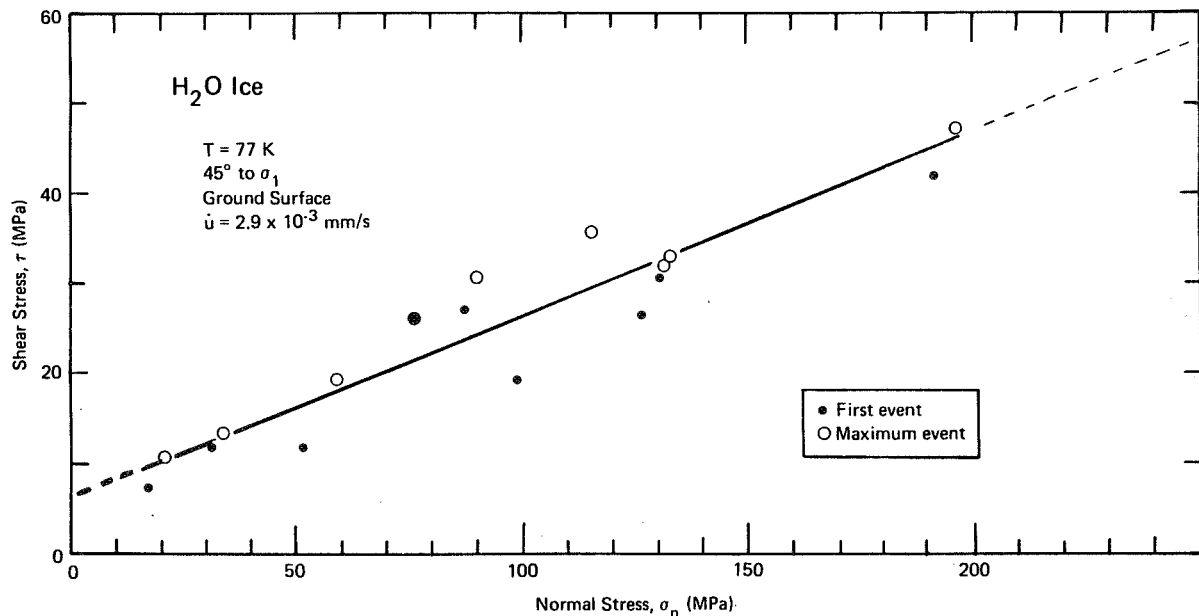
Fig. 3. Frictional strength of ice.

stress across the fault: the frictional strength rises
2 MPa for every 10 MPa increase in the normal stress (Figure
3). This strength is considerably less than that for most
rocks. Applying these results to icy moons, weaker fault
strength means increased tendency for deeper faults, that
is, the depth at which plastic flow becomes favored over
frictional sliding becomes deeper. Under extensional
stresses of the order of 10 MPa, sliding on existing faults
would be expected to extend to a depth of approximately 10
km in ice.

Effect of impurities on the flow of ice. This phase of
the project began very recently. The first series of tests
on samples of ice I_h from the important "intermediate"
temperature regime (243 K to 195 K) has shown unambiguously
that small amounts (less than 1%) of particulate impurities
have no effect on the plastic flow properties of ice. The
work will be extended to different temperature regimes,
different amounts of particulate impurities, and perhaps
different phases of ice. The study of dissolved impurities
in water ice, especially methane and ammonia, is the subject
of a current proposal to NASA.